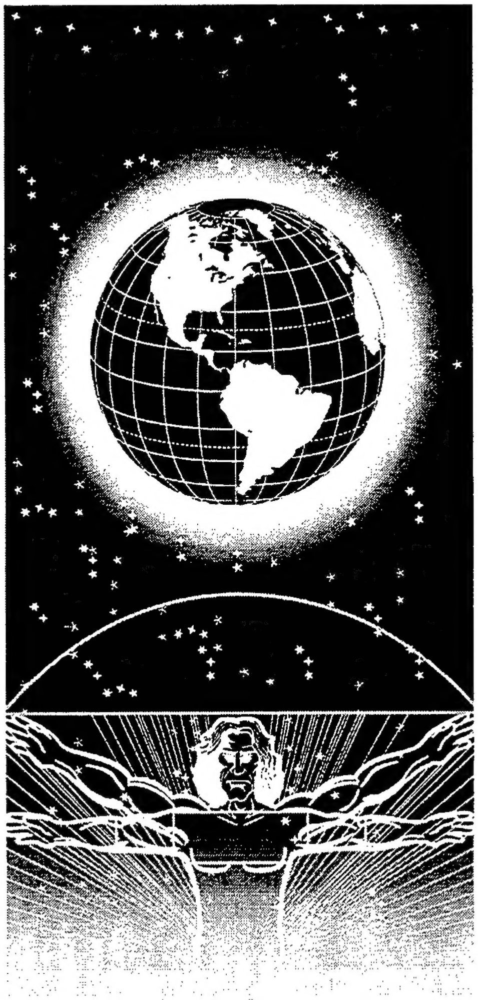
AFRL-HE-BR-TR-2001-0012



UNITED STATES AIR FORCE RESEARCH LABORATORY

OPERABILITY ASSESSMENT OF VARIOUS AGENT DEFEAT CONCEPTS USING PULSED POWER TECHNOLOGY

Johnathan L. Kiel

HUMAN EFFECTIVENESS DIRECTORATE
DIRECTED ENERGY BIOEFFECTS DIVISION
BIOMECHANISMS AND MODELING BRANCH
2503 Gillingham Dr.
Brooks AFB, Texas 78235-5104

February 2001

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Johnathan L. Kiel

JOHNATHAN L. KIEL, Ph.D.
Contract Monitor

Miller

RICHARD L. MILLER Ph.D.
Chief, Directed Energy Bioeffects Division

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-01-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
14-02-2001	Interim	From 15 May 2000 to 15 Nov 2000

4. TITLE AND SUBTITLE	
Operability Assessment of Various Agent Defeat Concepts Using Pulsed Power Technology	5a. CONTRACT NUMBER DTRA MIPR #00-2114
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 462D
6. AUTHORS Johnathan L. Kiel	5d. PROJECT NUMBER 253999
	5e. TASK NUMBER 88
	5f. WORK UNIT NUMBER 01145

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Air Force Research Laboratory, Human Effectiveness Directorate Directed Energy Bioeffects Division, Biomechanisms and Modeling Branch 2503 Gillingham Drive Brooks AFB, Texas 78235-5104	AFRL-HE-BR-TR-2001-0012
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
Defense Threat Reduction Agency 45045 Aviation Drive Dulles, VA 20166-7517	DTRA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report summarizes a large volume of data generated over the past 10 years on plasma decontamination. The intent was not to revisit this data in detail but to provide the big picture in order to evaluate the operational applicability of the pulsed-power methodologies addressed.

15. SUBJECT TERMS

Atmospheric plasma modalities
Chemical agents
Biological agents
Plasma decontamination

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Johnathan Kiel
					19B. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	8	(210) 536-3583

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

INTRODUCTION

Many directed energy sources have been proposed for the destruction of biological and chemical weapons (1). The effectiveness of such modalities has been based on the fact that biological and chemical agents are subject to oxidation, free radical inactivation, photochemical damage, and pyrolysis. However, what is usually not considered is the amount of energy required to destroy the mass of agents (in production or stored or contained in completed weapons). The vulnerability of a given agent is not only based on the intrinsic sensitivity of the agent to these insults but also upon the amount of agent and in what it is contained. The latter includes binders or diluents, weapon containers, and facilities, and the respective shielding they afford. All directed energy modalities are limited by two parameters: (1) the amount of energy that can be delivered and (2) the amount of time in which this can be accomplished. The first limitation is based on the directed energy source that is practicable in the field, in turn, based on portability, affordability, and availability. The second limitation is dependent to a large part upon the former. However, it is also dependent on the amount of directed energy required to kill the agent to the extent to render it safe. For example, if a source can kill 99% of the agent in milliseconds, but requires hours to finish the job (achieve greater than 5 logs of kill), then it would not be practicable in a munition or interceptor rocket. This notional idea is not absurd because the kill curves previously observed for a variety of directed energy sources produces just such "tails" (2). These tails are generated by different target sizes for the organisms or agent. The slope of the kill curve is directly proportional to the target size (such as the genome). To put this in perspective, 5 logs are equivalent to 99.9999% kill. In other words, this level of kill is equivalent to a 10^{-6} dilution of the agent. This arbitrary efficacy of kill is based on the fact that anthrax spores are usually produced at 10^{9} to 10^{10} spores per gram (3). A lethal dose of spores for a person is assumed to be 10^{4} spores (4). A five-log reduction would therefore decrease the lethal dose load of a gram of agent from 100,000 to 1 million lethal doses down to between 1 and 10. Of course, when kilograms of spores are delivered in a weapon, even 10^{5} kill may not be good enough. The resistance of microbes or molecules of toxin (chemical or biological) is more statistical than intrinsic. The shear number of targets predicts that there will be an appreciable number of "survivors" if the kill mechanism is not 100% or overkill for the amount of agent to be neutralized. With biological targets this is even more problematic because of the potential of repair from redundant broken "pieces" (5). Therefore, regardless of the fact that individual pieces of DNA are equally susceptible to damage by radiation, chemical, or thermal insults, they will not all be damaged in the same way at the same time. If they can recombine to form a functional agent, then because biological agents are used in such large quantities in high concentrations, even the most improbable repair event will occur. Furthermore, because biological agents (other than toxins) can reproduce, these rare repair events can become amplified by agent replication. Taking all the aforementioned information into consideration, pulsed power technology must be capable of overkill or provided the time necessary to complete neutralization. A "significant" level of kill by most scientific and statistical standards is probably insufficient to work operationally. Based on this reasoning, this report examines several concepts of pulsed power chemical/biological neutralization for operational applicability.

HIGH POWER MICROWAVE SOURCES

Unless a microwave source can achieve reliable, large-scale plasma generation and breakdown, it is unlikely that it will yield efficacy of kill sufficient to be a field able device. We have recently examined a high power microwave pulsed source (2 MW, 1.25 GHz) for its ability to kill anthrax spores (6). Depending on the culture recovery technique used, the exposure generated a 4-log kill

after a total of 54 msec of actual microwave exposure. This result sounds impressive. However, on non-selective growth medium, the spore recovery actually increased three times over the control. This result indicates that the spores were damaged and that the damage increased efficiency of germination on enriched growth medium. The recovery of damaged agent is exactly the point made in the introduction of this report that is so worrisome from an operational point of view. Therefore, if plasma generation is the mechanism of kill of anthrax spores (and probably less durable agents), then a more efficient method of its generation and application is necessary to overcome the limits of energy and time.

IONIZING RADIATION SOURCES (PARTICULATE AND PHOTONIC)

At first glance, ionizing radiation seems an ideal way to destroy biological agents and a less desirable way to destroy chemicals (1). However, it is even more problematic than other methods. Particulate (neutron) radiation has better penetration/energy transfer interaction and radiobiological effectiveness than photonic (gamma ray or X-ray) radiation (7). However, particulate radiation methods suffer from "too many small targets" in respect to killing microbial or chemical agents. The issue is not whether neutron radiation can destroy DNA or other molecular targets, but rather what density of particles and at what rate would be required and is it achievable. The situation worsens when one is talking about a weapon-to-weapon interaction (missile-to-missile kill). Achieving (and therefore, predicting) the appropriate dose and dose rate to accomplish the necessary overkill is a major aspect of designing a useful anti-agent ionizing radiation weapon. Such a weapon would have greater utility and efficacy if it could be applied over a long time and could also utilize the heat output as a secondary mechanism for agent kill. Heat plus ionizing radiation destroys repair processes of damaged DNA (8). Therefore, the utility in the field of ionizing radiation is best suited for stationary sources in contact or near to chemical/biological production/storage facilities. Such devices would not be detonated munitions but radiative sources placed in proximity to the facilities and their contents.

Ionizing radiation sources can be considered multi-mechanistic in their attack on microbial and molecular targets. The radiation not only directly breaks bonds, but also ionizes water and other materials producing secondary free radicals that can damage DNA, proteins, and cell membranes (1, 7). These secondary reactions are chemical and, therefore, diffusion limited, bringing us back to the density problem. The ionizing source can also, if given sufficient time, provide substantial thermal energy to damage chemical/biological targets. If any ionizing methodology is to be used, then neutron is preferred because of the high density of particulate radiation that can be achieved. However, it is unlikely, at the present state-of- the-art, that a missile-to-missile encounter would provide sufficient time or distance to achieve the very high efficiency of kill necessary to sufficiently neutralize a biological or chemical weapon.

COLD PLASMA SOURCES AND THEIR APPLICATIONS

Plasmas are usually considered products of very high energy and high temperature processes (9). However, when non-equilibrium conditions are imposed on plasmas such that the electrons have a much higher energy (high electron temperature) than the heavy particles, then the plasma is referred to as cold plasma. Plasmas could kill by a number of mechanisms including heat, chemical reaction with radicals or meta-stable species, electric field pulses, pressure field pulses, exposure to high energy photons in the ultraviolet or x-ray region, or direct exposure to particles with high energies. These mechanisms are in common with many of those produced by ionizing radiation sources mentioned above, but without the real or perceived hazards associated with ionizing radiation. Cold plasmas kill most efficiently primarily by the reactive chemical method.

This is fortunate for decontamination methodologies because it does less damage to materials. Unfortunately, until recently most atmospheric pressure and air-utilizing plasma devices generated an inordinate amount of ozone. Ozone is both toxic to humans and damaging to materials. Unfortunately, it is not very effective against microbes or chemicals unless water or another suitable solvent is present (9). The principal active agents in plasma are ozone, mono-atomic oxygen, and meta-stable singlet delta oxygen. Mono-atomic oxygen is the most active, but quickly recombines with other oxygen atoms to form diatomic oxygen or ozone. Singlet delta oxygen forms by collision with electrons or other excited species and has a relatively long lifetime of 0.1 to 1 second at atmospheric conditions. Ozone is fairly fragile, being dissociated by collisions with electrons or other excited species within the plasma. Outside of the plasma device, especially those using air as the gas source, ozone can be long lived. Ozone production is strongly correlated with non-uniform, large energy gradient systems such as arcs and with photo-dissociation related to the devices' production of ultraviolet light.

There are many types of plasma discharge devices including arcs, corona, glow, dielectric barrier, plasma torch, microwave, and low pressure. Direct current or alternating current fields from a few KHz to GHz frequencies generate these discharges. The electron temperature and electron number density characterize the plasma discharges. Arcs have number densities of 10^{16} to 10^{19} cm^{-3} and gas and electron temperatures of about 10,000K. Corona, glow discharges and plasma jet discharges have electron number densities of 10^{9}-10^{14} cm^{-3}. Electron temperature in corona, glow, or jet discharges is from 10,000K to 70,000K. The gas temperatures are below 600K. The lower temperatures are probably achieved by decoupling of energy between electrons and heavy ionic species. The power required to sustain plasma is directly proportional to the electron number density. The low number densities are therefore desirable to meet power requirements for portability and field use. However, the tendency for these devices to generate ozone must be controlled. Varying the pressure, temperature, oxygen/nitrogen mixture, electric field strength, and power density can control reactions and reaction rates. This would allow for a more optimal killing mixture of singlet oxygen and ozone to be produced.

Besides the ozone production problem with plasma, power supply is a consideration. An example device, the one atmosphere uniform glow discharge plasma device, requires a power supply of 1-10 kHz at 10 kV at 6 kW. Electrocution is an immediate operational concern with this device. The supply could deliver 600mA at 10 kV. The atmospheric pressure plasma jet, another example, operates at 13.56 MHz with less voltage, but with a problem of radio frequency radiation leakage. Another device that yields better portability and less of an electrocution risk is the plasma corona reactor. (10). It has a variable gas flow rate, operating power up to 1 kW, maximum pulse voltage of 10kV to 30 kV, and a variable pulse repetition rate up to 2 kHz. The power supply generates a current of 0.05 amperes. The generator uses house air and generates plasma that is effective at room temperature. At 40 watts, preliminary experiments with this reactor examining the killing of dry anthrax spores showed a 90% kill at 5 min and a 100% kill at 30 min of operation. The killing was not only within the reactor, but also at the exhaust port, indicating the production and release of a stable gaseous killing agent. The exhaust port samples actually were killed more quickly than those at different locations within the reactor. One hundred per cent kill was achieved repeatedly within 10 minutes at the exhaust port. The killing of anthrax spores in the corona discharge device at 20 to 100C for 5 min was equivalent to that observed for thermal killing of anthrax spores at 100C for 2.5 hours (6). Pulsing should decrease the ozone production, minimize the power requirement, and lead to a more portable device. The fact that the exhaust as well as the interior gases kills anthrax spores indicates that the device can be used in the "vacuum cleaner" and "leaf blower" format.

Major objections to plasma decontamination were raised by a US Army sponsored report in 1990 (9). These were an almost total lack of data on chemical by-products produced by plasma devices, the ability of plasma to be used as an offensive weapon by attacking forces or by turning it against those using it for decontamination by introducing certain aerosols or gas mixtures, and

the magnitude of post-processing required in the context of a military-deployable system. The report also raised the issue of power requirements in the field. However, a Front End Analysis of Decon held at Edgewood Chem/Bio Center in December 1998, clearly pointed out that atmospheric plasma modalities had the widest operational applicability. Currently (FY01), the Air Force Research Laboratory has initiated an exploratory research project to look at the chemical and biochemical products of corona plasma discharge operation, including those produced in the presence of various biological and chemical agents. This will address a major concern of the initial Army report. Furthermore, the technology has undergone considerable change since the report that deserves revisiting its application.

CONCLUSIONS

This report has summarized a large volume of data generated over the past 10 years on plasma decontamination. The intent was not to revisit this data in detail but to provide the big picture in order to evaluate the operational applicability of the pulsed-power methodologies addressed. The necessity for overkill to assure safe levels after the application of a countermeasure in the case of chemical/biological weapon destruction dictates the use of multiple kill mechanisms and redundancy. A 99% kill is not sufficient when dealing with grams to kilograms of a highly toxic agent or a biological agent that can repair and reproduce itself. When the pulsed power sources are considered in toto, they all utilize free radical generation, chemical activation, and heat to varying extents to kill agent. A combination of these mechanisms rather than a single one is required to overcome the repair processes in microbes and to assure complete destruction of agent. The limits on the use of any given pulsed power source, therefore, are the health and safety of the operators, the portability of the source, and its power requirements, not the mechanism of interaction.

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